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The Generation, Use, and Misuse of "PKs" in Vulnerability/Lethality Analyses

by Paul H. Deitz
and Michael W. Starks

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Abstract

Beginning with World War II and its aftermath, the area of ballistic vulnerability/lethality (V/L) was first defined as a specific discipline within the field of ballistics. As the field developed, various practices and metrics emerged. In some cases metrics were developed that were abstractly useful but bore no direct relationship to field observables. In the last decade, as issues concerning Live-Fire strategies have gained importance, increased attention has been focused on V/L with the intent of bringing greater rigor and clarity to the discipline. In part this effort has taken the form of defining a V/L Taxonomy, which is a method of decomposing a series of concatenated complex processes into separable, less-complex operations, each with certain specifiable properties and relationships.

Using the Taxonomy, this report describes the most commonly used V/L metrics are a function of platform *aggregate damage*, reduced platform *capability*, and reduced *military utility*. We show that these three distinct and separable classes of metrics are linked by operators that are multivariate, stochastic, and nonlinear. We also show that it is useful to form probability distributions with respect to initial and boundary conditions in order to characterize damage, capability, and utility. Many defense community studies ignore these distinctions to the detriment of fundamental clarity. Examples are given and potential remedies described.

Preface

This report is an expanded version of a paper presented at the 8th Annual Tank-Automotive Research, Development, and Engineering Center Symposium, held at the Naval Postgraduate School in Monterey, CA, 25–27 March 1997.

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ABSTRACT

Beginning with World War II and its aftermath, the area of ballistic vulnerability/lethality (V/L) was first defined as a specific discipline within the field of ballistics. As the field developed, various practices and metrics emerged. In some cases metrics were developed that were abstractly useful but bore no direct relationship to field observables. In the last decade, as issues concerning Live-Fire strategies have gained importance, increased attention has been focused on V/L with the intent of bringing greater rigor and clarity to the discipline. In part this effort has taken the form of defining a *V/L Taxonomy*, which is a method of decomposing a series of concatenated complex processes into separable, less-complex operations, each with certain specifiable properties and relationships.

Using the Taxonomy, this report describes how the most commonly used V/L metrics are a function of platform ***aggregate damage***, reduced platform ***capability***, and reduced platform ***military utility***. We show that these three distinct and separable classes of metrics are linked by operators that are multivariate, stochastic, and nonlinear. We also show that it is useful to form probability distributions with respect to initial and boundary conditions in order to characterize damage, capability, and utility. Many defense community studies ignore these distinctions to the detriment of fundamental clarity. Examples are given and potential remedies described.

INTRODUCTION

Beginning with World War II and its aftermath, the area of ballistic vulnerability/lethality (V/L) was first defined as a specific discipline within the field of ballistics. As the field developed, various practices and metrics emerged. Certainly the best-known metrics normally produced by the V/L community are "PKs" or "Probability of Kills." Following the establishment of Live-Fire regulation[1] in the last decade, the concomitant issues of Live-Fire Test (LFT) strategies and model verification, validation, and accreditation (VV&A) have gained importance. Increased attention has been focused on V/L with the intent of bringing greater rigor and clarity to the discipline. For example, some of the V/L metrics used for many years and commonly referred to as "PKs" are not probabilities at all but are a kind of expected-value utility function, constructed with the aim of describing the battle value of a damaged platform. However, long-standing practice in the wargame modeling communities has been to use these numbers as probabilities.

The outcomes of actual live-fire field shots have often been assessed in terms of probabilities of kill, in spite of the fact that what has been observed is in fact a single outcome from a probability space. This practice is conceptually equivalent to reporting a football game outcome after the fact in terms of a probability of win.

The particular focus of this report is on the proper coupling of V/L metrics with wargames and other emerging forms of distributed force-level simulation. Our purpose here is not to decry the methods and practices of our forebears, but rather to describe a logical set of steps associated with the practice of V/L, and how they now might be implemented in the emerging world of increasingly powerful computers, high-level architectures, and distributed interactive simulations.

1. *Live Fire Testing*, National Defense Authorization Act for FY 1987, Chapter 139, Section 2366 of Title 10, United States Code.

V/L FRAMEWORK

We recall that vulnerability generally refers to the assessment of damage and dysfunction visited on a blue (friendly) military platform. By contrast, lethality generally refers to the assessment of damage and dysfunction on a red military platform. Starting about a decade ago, we have asserted that the study of vulnerability can be separated into four fully separable and sequential levels or spaces each connected with a mapping operator. These notions are explained in detail elsewhere,[2-4] and we build upon those ideas here.

The totality of vulnerability can be partitioned among three kinds of descriptors: (1) damage to the target, (2) loss of platform (*i.e.*, target) functional capability, and (3) reduction in battlefield utility. Each of these descriptors is characterized using the V/L Taxonomy abstraction.

Levels, Operators, and Mapping Abstraction

Figure 1 illustrates six levels (or mathematical spaces) labeled **Level -1]** through **Level 4]**. Each **Level** represents distinct and separable classes of observables covering the gamut of weapons effectiveness. Each bullet in a **Level** represents a vector, which is characterized by a set of physical parameters. The composition of the vectors at each level is particular to the **Level**. A vector at one **Level** can be mapped to a vector at the next **Level** by an **Operator**. The operators are represented by the notation $\mathbf{O}_{\mathbf{p,q}}$, in which **p** represents the **Level** on which the input vector ($\mathbf{v}_{\mathbf{p}}$) resides and **q** denotes the **Level** on which the output vector ($\mathbf{v}_{\mathbf{q}}$) resides. Thus a vector at the **p** level can be written:

$$\mathbf{v}_{\mathbf{q}} = \mathbf{O}_{\mathbf{p,q}}\{\mathbf{v}_{\mathbf{p}}\} \quad . \tag{1}$$

It is important to understand that the vector $\mathbf{v}_{\mathbf{q}}$ has specific observable physical or engineering properties and *is not a probability*. However, the operator $\mathbf{O}_{\mathbf{p,q}}$ is normally stochastic, so probability distributions can be *inferred* by repetitively operating on a single $\mathbf{v}_{\mathbf{p}}$ vector in order to generate a population of $\mathbf{v}_{\mathbf{q}}$ vectors.

$O_{1,2}$ Mapping

For reasons that become clear later, we will start with **Level 1]** as depicted in Fig. 1. Each bullet within the space of **Level 1]** represents a vector describing the warhead (or threat) and target (including kinematics) as a vulnerability event is initiated. Table I gives a listing of the levels, vectors, and vector descriptors. A useful way to view the vector $\mathbf{v}_{\mathbf{1}}$ is as a descriptor for the initial conditions for a live-fire shot. The operator $\mathbf{O}_{\mathbf{1,2}}$ is the nonlinear, multivariate, stochastic operator that maps live-fire initial conditions to **Level 2]**, damaged components.

At **Level 2]** the outcome space of vectors represents the list of platform components either not killed (□) or killed (■).[‡] This information is extremely valuable and provides the foundation for all further vulnerability. The damage vector enumerates crew casualties, ammunition, and fuel catastrophic events and the status of all other critical and ancillary components on board the platform. At this point platform survivability is assessed. One of the lessons learned from live-fire and the supporting modeling efforts is that the outcome space at **Level 2]** is large. For some overmatching munitions against armored ground vehicles, we estimate an outcome space in excess of

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2. Paul H. Deitz and Aivars Ozolins, *Computer Simulations of the Abrams Live-Fire Field Testing*, **Proceedings of the XXVII Annual Meeting of the Army Operations Research Symposium**, 12-13 October 1988, Fort Lee, VA; also **US Army Ballistic Research Laboratory Memorandum Report BRL-MR-3755**, May 1989.

3. J. Terrence Klopcic, Michael W. Starks, and James N. Walbert, *A Taxonomy for the Vulnerability/Lethality Analysis Process*, **US Army Ballistic Research Laboratory Memorandum Report BRL-MR-3972, May 1992.**

4. Paul H. Deitz, *A V/L Taxonomy for Analyzing Ballistic Live-Fire Events*, **Proceedings of the 46th Annual Bomb & Warhead Technical Symposium**, 13-15 May 1996, Monterey, CA; also appears in *Modeling Ballistic Live-Fire Events Trilogy*, **US Army Research Laboratory Technical Report ARL-TR-1274**, December 1996.

‡ Throughout the V/L business there is a seminal issue that involves the characterization of damage. In the extreme, the analyst can choose damage descriptors that are either Bernoulli in outcome (kill/no-kill) or fractional (values 0.0 ≤ [Fractional Capability] ≤ 1.0). This issue arises not only with component damage at **Level 2]** but with platform capability at **Level 3]** as well. The Army Research Laboratory generally uses the Bernoulli method to describe component dysfunction for a number of theoretical and pragmatic reasons. This issue is discussed further in Paul H. Deitz, Jill H. Smith, and John H. Suckling, *Comparisons of Field Tests with Simulations: Abrams Program Lessons Learned*, **Proceedings of the XXVIII Annual Meeting of the Army Operations Research Symposium**, 11-12 October 1989, Fort Lee, VA, pp. 108-128; also **US Army Ballistic Research Laboratory Memorandum Report BRL-MR-3814**, March 1990. See also the Appendix to Ref. 14.

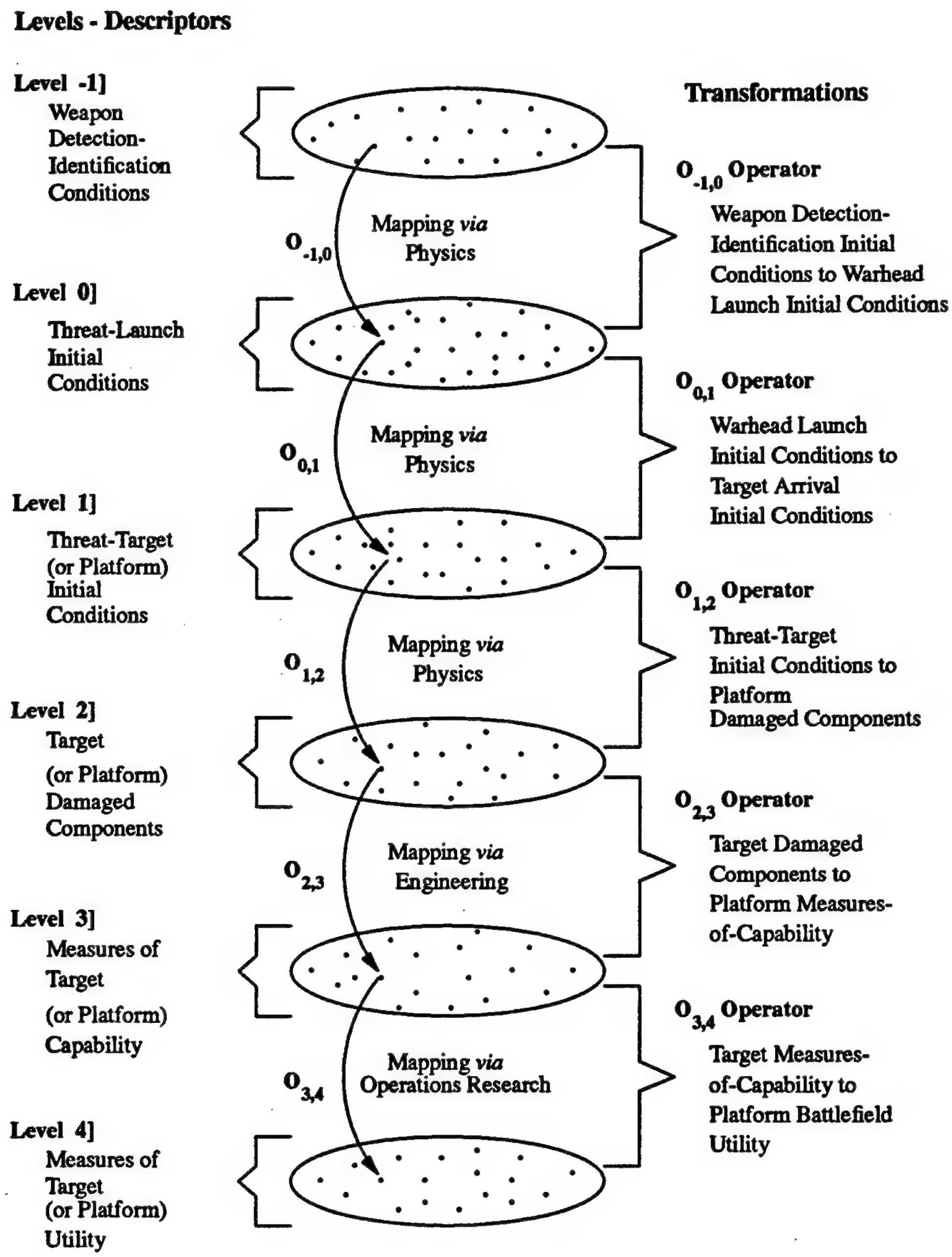

Fig. 1. V/L Taxonomy illustrated via a Mapping Abstraction. The ellipses in the middle column represent mathematical spaces. The bullets (•) contained within the spaces represent vectors (represented elsewhere in the paper as v_p). The arrows represent mapping operators that take a vector at one **Level** and perform a mapping to the next lower **Level**. On the left, the descriptors for the various **levels** are given; on the right, the actions of the various operators. Note the single connected path of arrows from **Level -1]** to **Level 4]** represents a single sample in an end-to-end connected process. As shown here, the initial conditions at **Level -1]** could be drawn stochastically or input deterministically. Since many of the succeeding operators (**$O_{-1,0}$** to **$O_{3,4}$**) are stochastic, the results from **Level 0]** through **Level 4]** usually represent a set of connected stochastic metrics in outcome space.

Level	Vector	Vector Descriptors
-1]	v_{-1}	**Physical Characteristics Leading to Decision to Fire**
0]	v_0	**Physical Characteristics of Threat at Launch**
1]	v_1	**Threat Geometry & Material,** **Platform Geometry & Material,** **Threat Kinematics & Orientation vs. Platform**
2]	v_2	**Status of Platform Damage:** ***i.e.*, Non-Killed (□) and Killed (■) Components** **→ Platform Survivability**
3]	v_3	**Platform Capability:** ***e.g.*, Mobility, Firepower, and Commo Functions**
4]	v_4	**Platform Utility:** ***e.g.*, Does Platform Survive? (From Level 2]),** **Does Platform Perform Specific Mission?**

Table I. Composition of Vectors at Each Level. In the left column are the levels corresponding to those shown in Fig. 1. In the middle are the related vector symbols. On the right are descriptions of the vector compositions at each level.

30×10^6. This makes model validation problematic for multiple reasons. The size of the outcome space precludes exercising the model sufficiently even to compute a simple majority of the possible predicted outcomes. Having normally only a single field outcome to compare with the model provides limited utility.

$O_{2,3}$ *Mapping*

As noted in Fig. 1, the $O_{2,3}$ operator takes a **Level 2]** damage vector and maps it to a platform-level capability vector at **Level 3]**. Such vectors are normally measurable quantities that relate directly to the ability of the platform to support particular mission functions. Table I lists **Mobility**, **Firepower**, and **Communication** as examples. In a later section, we further refine these capabilities and show how they can be appropriately linked to a wargame. The $O_{2,3}$ mapping process was developed at the US Army Research Laboratory (ARL) over the past decade[5,6] and is called the Degraded States Vulnerability Methodology. The methods have been applied to a number of ground[7] and air systems.[8] Additionally, this mapping replicates the Reliability, Availability, and Maintainability (RAM) process[9] as well as the inverse path needed to effect the repair of battle damage. We suggest that **Level 3]** metrics correspond to what the Operations Research community normally refers to as Measures-of-Performance (MoPs).

5. John M. Abell, Lisa K. Roach, and Michael W. Starks, *Degraded States Vulnerability Analysis*, US Army Ballistic Research Laboratory Technical Report BRL-TR-3010, June 1989.
6. Lisa K. Roach, *The New Degraded States Vulnerability Methodology (DSVM): A Change in Philosophy and Approach*, US Army Research Laboratory Technical Report ARL-TR-1223, November 1996.
7. John M. Abell, Mark D. Burdeshaw, and Bruce A. Rickter, *Degraded States Vulnerability Analysis: Phase I*, US Army Ballistic Research Laboratory Technical Report BRL-TR-3161, October 1990.
8. Robert W. Kunkel, Jr., *Degraded States and Fault Tree Analysis of the LONGBOW APACHE (LBA)*, US Army Research Laboratory Technical Report ARL-TR-801, July 1995.
9. Lisa K. Roach, *Fault Tree Analysis and Extensions of the V/L Process Structure*, US Army Research Laboratory Technical Report ARL-TR-149, June 1993.

$O_{3,4}$ Mapping

In order to execute properly the $\mathbf{O}_{3,4}$ mapping, we need to move into the context of a wargame. The platform under scrutiny is located in a certain place/time. A specific set of tactics and doctrine is in operation, and a specific scenario is being realized. Let us assume our platform has received exactly one hit. This action has (presumably) caused some number of components to have been killed and, as a result, some loss of capability at **Level 3]**. The operator $\mathbf{O}_{3,4}$, based on the next mission of the game, calls for a particular action. This action would normally be within the capability of an undamaged platform. If the damaged platform can nevertheless still perform the action, it retains its battlefield utility. If not, the platform fails. We describe a notional example of this process near the end of the report. We believe that **Level 4]** metrics correspond to what the Operations Research community normally refers to as Measures-of-Effectiveness (MoEs).

We have posed this process in the context of a platform receiving its ***first*** hit and ***first*** damage. In addition to the problematic way most current **Level 4]** metrics are constructed,[∞] they are normally used as a basis for a random draw in the context of the wargame. If the draw is true, the vehicle is withdrawn from the game. If not, it continues undamaged. Multiple hits of like kind or damage from other threats (*e.g.*, chemical, nuclear, electromagnetic) are all posed as PKs, under the assumption that no prior damage has occurred to the platform. These multiple hits are normally processed *via* the *Survivor Rule.*[‡] Thus, in addition to the individual metrics being flawed, combining a sequence of damages without regard to the fact that they have been each calculated using a pristine (*i.e.*, undamaged) platform and combining damage without regard to the order in which it has occurred by aggregation are problematic.[□]

$O_{0,1}$ Mapping

We have so far described the process of vulnerability beginning with **Level 1]**. The V/L Taxonomy was originally generated in order to investigate the process of vulnerability. Standard practice in vulnerability is to ***assume*** a particular warhead hit condition. This is why the level for vulnerability initial conditions is labeled **Level 1]**.

By contrast, lethality often includes a prefactor in vulnerability, the warhead hit dispersion. Thus in Fig. 1, we have added **Level 0]** to connote the warhead launch initial conditions and the operator $\mathbf{O}_{0,1}$, which takes the warhead and computes the dispersion statistics as input (as needed) to **Level 1]** for a subsequent $\mathbf{O}_{1,2}$ computation.

$O_{-1,0}$ Mapping

For completeness, we have added **Level -1]**. This is the level in which the inputs into the target detection and identification processes fit. The operator $\mathbf{O}_{-1,0}$ takes the relevant initial conditions and maps them both to a decision to fire and the configuration of the threat launcher.

Stochastic Mapping, Repeated Sampling, and Probabilities

Turning our attention once again to Fig. 1, we have described six levels connected by five mapping operators. Although some of the operators are stochastic,[§] no vector outcome at any of the **Levels** is a probability. The set of connected mapping arrows begins by initiating an action at **Level -1]** and carries the continuous thread through to Military Utility at **Level 4]**. If probability distributions are needed at any particular level, they can be *inferred* by repetitively initiating model runs beginning at least one **level** above the particular **level** of interest.

∞ As we discuss later, most ground-system PKs actually begin life as a "fractional loss of battlefield utility" and then are averaged over a wide range of weighted missions. They are mistakenly assumed equivalent to and used as PKs.

‡ The Survivor Rule as used here states that the overall PK for a platform attacked by *n* independent threats, each characterized with its own PK_i, is given by:

$$PK = 1-\Big[[\,1-PK_1\,]\times[\,1-PK_2\,]\times\cdots[\,1-PK_n\,]\Big] \quad .$$

□ Lest the reader think this is not a problem, consider the cases of (1) an artillery attack on an armored personnel carrier (APC) that causes a number of perforations to the armor but otherwise does no damage, followed by (2) the deposit of a chemical agent on the APC. These attacks when assessed *independently* against the APC have no effect. When assessed together, the outcome might be very different.

§ Operators $\mathbf{O}_{-1,0}$, $\mathbf{O}_{0,1}$, and $\mathbf{O}_{1,2}$ are fully stochastic. The representation of the $\mathbf{O}_{2,3}$ operator *via* the current Degraded States Vulnerability Methodology is currently deterministic. The $\mathbf{O}_{3,4}$ mapper could be implemented either way. A deterministic method would probably be adequate.

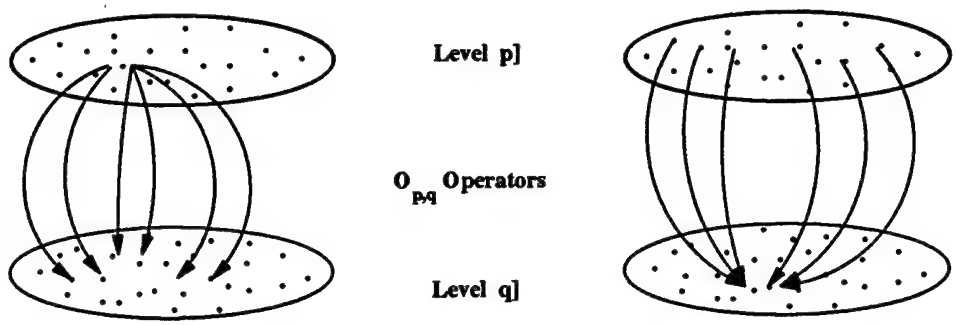

Fig. 2. Examples of Expansive and Contractive Mappings. On the left is an example of multiple mappings that go from few to the many. On the right is an example of multiple mappings that go from many to few.

In order to gain a sense of how the stochastic replications might behave, we refer to Fig. 2. On the left is an example of what might be called an Expansive Mapping. In this case, a single set of inputs (indicated by a single vector at **Level p]**), when repetitively mapped, will tend to terminate at different vectors (at **Level q]**). Our modeling experience tells us that the Operators $\mathbf{O}_{-1,0}$, $\mathbf{O}_{0,1}$, and $\mathbf{O}_{1,2}$ can be expected to behave this way. The $\mathbf{O}_{2,3}$ operator, as implemented *via* Degraded States, is deterministic and strictly a one-to-one mapping. Since the dimensions of **Level 3]** are far lower than **Level 2]**, the $\mathbf{O}_{2,3}$ operator and most likely the $\mathbf{O}_{3,4}$ operator will have the effect of contracting the number of vectors in the outcome levels. This behavior is illustrated on the right of Fig. 2.

The overall picture one can gain from the process when repetitively sampled from top to bottom is one in which the population of vectors grows rapidly through **Levels 0]** through **2]** and then contracts rapidly through **Levels 3]** and **4]**. The very magnitude in the population of the intermediate levels attests to the specific nature of the vectors at a given level and the way in which they feed into the ensuing operator. Clearly, unless these statistics are understood very well for the ranges of needed parameters, averaging at too low a level can place ensuing results in doubt.

Lethality Contrasted with Vulnerability

Previously we noted some typical differences between the way lethality and vulnerability are normally construed. In Fig. 3, we have reproduced the six levels and have attempted to show how various descriptive labels are normally used by the community at large.†

Although many of the tools for V/L are commonly shared, there are differing motives for those who develop weapons (*e.g.*, missiles and gun munitions) and examine lethality *vs.* those building military platforms (*i.e.*, ships, tanks, aircraft) who focus on vulnerability. The concerns of the former are shown on the left from the standpoint of **Threat-Lethality Orientation.** The concerns of the latter are shown on the right from the standpoint of **Platform-Survivability Orientation.** From the standpoint of weapons optimization, **Lethality** is shown as beginning with the weapon launch. Overall **Effectiveness** might extend the process back one level to include Target Detection-Identification. From the standpoint of platform survivability, vulnerability is shown as the end-game process *beginning* with the munition hit. **Susceptibility** can be viewed as all of the prior processes that lead to the hit initiation at **Level 1]**. **Survivability** can be viewed as the end-to-end process in which susceptibility and vulnerability are combined.

One important manifestation of the difference in which these two communities view their need sets can be seen in the context of Live Fire. A Project Manager (PM) developing a new missile seeks assurance that the missile will be sufficiently lethal against a given target class. The need includes sufficient overkill so that future enemy countermeasures will not easily obviate weapon effectiveness. The details about the target damage or target function are probably not of great concern. By contrast, a PM developing a blue platform is likely to desire very specific information on both the damage (**Level 2]** information) as well as performance changes (**Level 3]** information) in order to

† For example, the V/L Taxonomy illustrated in Fig. 1 can be thought of as more formal representation of the following vulnerability reduction saying, well-known for at least two decades throughout the DoD vulnerability community: "Don't be detected, but if detected, don't be hit. If hit, don't be perforated. If perforated, don't be damaged. If damaged, don't be killed."

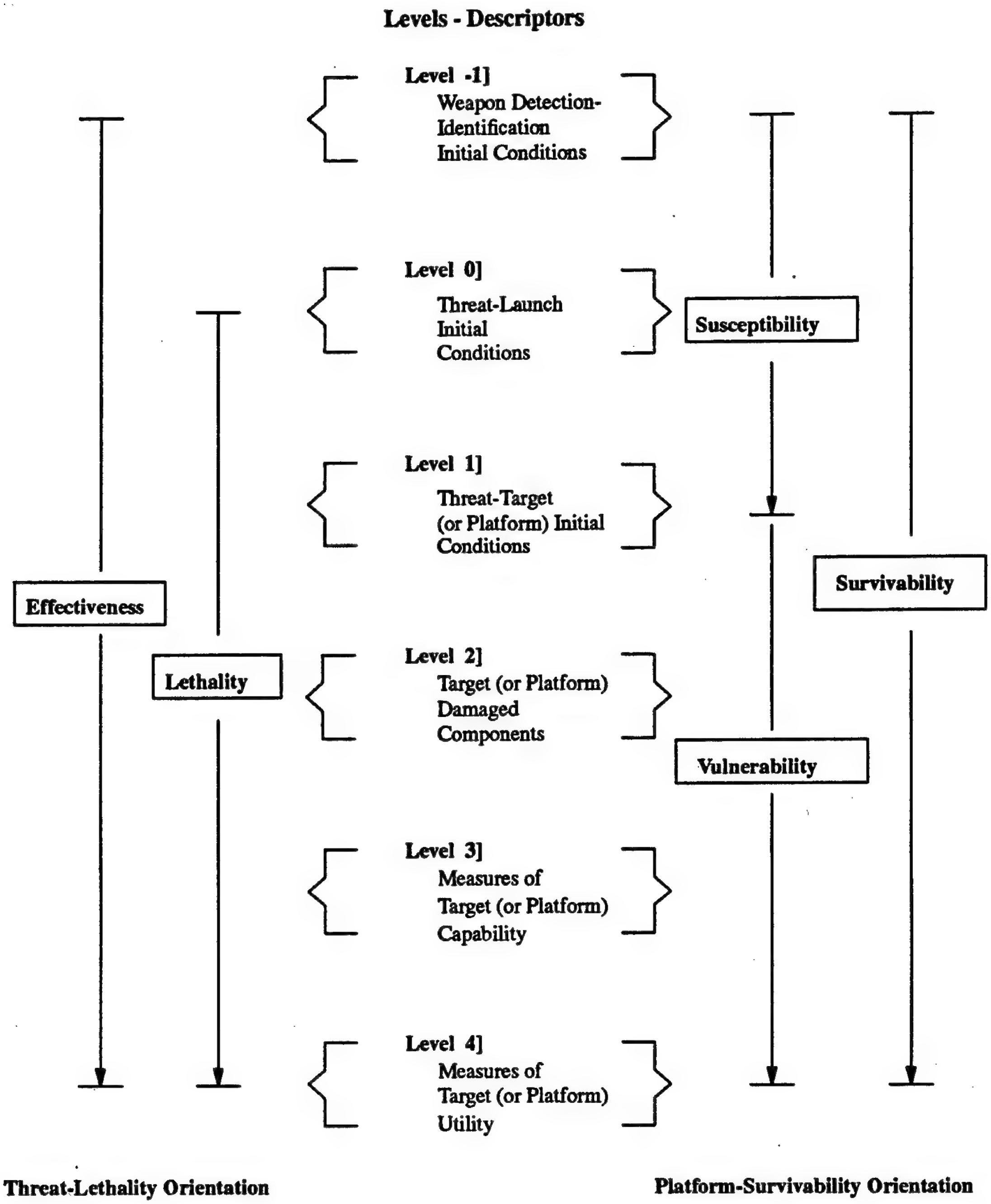

Fig. 3. Levels of Relevance to Lethality and Vulnerability. Lethality and Vulnerability are often used to pursue different agendas. Typically, **Lethality** is analyzed beginning with the weapons launch at **Level 0]**. Thus, warhead hit dispersion at the target is factored in. To estimate complete weapons **Effectiveness**, weapon target detection and identification must be included as well. By contrast, **Vulnerability** normally starts with an assumed hit at **Level 1]**. **Susceptibility** covers all of the prior factors leading up to a hit. **Survivability** provides the overall accounting.

assess crew casualties as well as platform effectiveness and the possibility of eliminating/mitigating damage through potential design variants.

PAST WARGAME EFFECTIVENESS PRACTICE

In what follows, we criticize past and existing practice concerning the representation of attrition in force-level combat models, simulations, and wargames. Fairness requires us to acknowledge, however, that much of what we find objectionable in current methods of attrition modeling was in the first instance promoted by mistakes and unclarities within the technical V/L community. In prior decades, the comparatively limited capabilities of computing hardware/software contributed to pressures to keep methods simple. We have written concerning these problems elsewhere; the point here is to present a top-level view of the difficulties so that the relationship with the consequent problems with force-level attrition can be clearly seen.

As suggested previously in the INTRODUCTION, one of the early problems concerned lack of clarity in distinguishing probability of kill from the military utility of a system with other than full capability. We have criticized the identification of PK and utility in detail elsewhere for the cases of tank vulnerability,[10] personnel vulnerability,[11] and V/L issues for other classes of targets.[12] Without repeating those arguments here, suffice it to say that questions and methods for dealing with our probability of winning the lottery are quite different from those appropriate to evaluating the utility of holding a winning ticket.

We assert that our predecessors viewed the problem in the following way. If vulnerability metrics were characterized as probabilities — even if mistakenly — significant advantages accrued. An aura of mathematical respectability was cast over what was an intrinsically flawed intellectual process. The probability calculus was made available as an instrument for numerical manipulation. In particular, one could multiply average hit probabilities by the average probability of kill given a hit values to obtain average single-shot kill probabilities (SSPKs). We can have both appropriate utility and mathematical consistency as well. There is a tortured history concerning the use of SSPKs that directly bears on the usual methods for transferring V/L information from technical data providers to force-level users. Before turning to that part of the story, however, let us dwell a bit longer on the internal intellectual problems with the technical V/L community.

One of these problems is early averaging. Even if we put to one side the illegitimate running together of probabilities and utilities that the SSPK example illustrated, early averaging remains a problem. Some of the problems with use of averages as V/L metrics are just mistakes; in other cases, the fault is needless loss of valuable information. One mistake is to endeavor to compare the outcome of a test or simulation event with an average probability.[§] Pollard *et al.*[13] made this mistake concerning LFT prediction and were criticized by Starks.[14] Another mistake is to average PK or SSPK over scenarios and other variables and then use that PK in a single one of those scenarios; this is simply an inconsistency, and one that in many cases infects the traditional V/L to force-level handoff.

The problem of needlessly lost information through early averaging can be particularly frustrating for analysts who encounter it. This is so because, as the discussion of the Taxonomy showed, the information lost was necessarily at hand during an intermediate point in the computation. Suppose we are conducting a study of armored vehicles where it is important to know the status of each sight. In **Level 2]** we clearly have a damage vector that reflects whether a given sight is functioning or not. If we drop this information after we have used it to calculate an average mobility or firepower utility, then it is obviously not available to answer specific questions about sights. It may have

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10. Michael W. Starks, *New Foundations for Tank Vulnerability Analysis (with 1991 Appendix)*, **The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association**, Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988; also **US Army Ballistic Research Laboratory Memorandum Report BRL-MR-3915**, May 1991.

11. Michael W. Starks, *Improved Metrics for Personnel Vulnerability Analysis*, **US Army Ballistic Research Laboratory Memorandum Report BRL-MR-3908**, May 1991.

12. Paul H. Deitz, Michael W. Starks, Jill H. Smith, and Aivars Ozolins, *Current Simulation Methods in Military Systems Vulnerability Assessment*, **Proceedings of the XXIX Annual Meeting of the Army Operations Research Symposium**, 10-11 October 1990, Fort Lee, VA; also **US Army Ballistic Research Laboratory Memorandum Report BRL-MR-3880**, November 1990.

§ Presumably no one in Green Bay, WI, has characterized the outcome of the 1997 Superbowl in terms of a Packer Probability of Win!

13. Ray G. Pollard, Gary L. Holloway, Dennis C. Bely, F. Tyler Brown, and J. C. Kisko, *An Examination of Vulnerability Predictions in Light of Live Fire Testing of Light Combat Vehicles*, **The 17th TWG/AOR Quadrapartite Working Group, for AOR**, held in Sidney, Australia, December 1987.

14. Michael W. Starks, *Assessing the Accuracy of Vulnerability of Models By Comparison with Vulnerability Experiments*, **US Army Ballistic Research Laboratory Technical Report BRL-TR-3018**, July 1989.

been reasonable to drop such information in an era when large numbers of computer cycles and storage were less available than they are today; it is not reasonable or efficient to do so now.

FORCE-LEVEL ISSUES

As indicated previously, **Level 4]** is concerned with military utility. A little reflection quickly shows that it is comparisons of systems with respect to military utility that allow top-level procurement decisions to be made and justified. Comparisons of lists of components (**Level 2]**) or of relative capabilities (**Level 3]**) do not allow or support this type of decision making. We do not try to rigidly define "military utility" here. Clearly, however, it has to do with prosecuting and winning engagements, battles, and wars. If the issue is readiness or tactical training, system procurement decision making, or examination of operational alternatives for achieving a strategic goal, then military utility, rather than a more narrowly drawn technical characteristic, is the proper metric for facilitating decisions.

We believe that military utility must be observed, measured, counted, or calculated in the context of actual or simulated force-level engagements, battles, and wars. This seemingly innocuous belief is in fact inconsistent with much of the past practice in the technical V/L arena. Recall that **Level 4]** metrics such as SSPK were taken as reflecting military utility and that they were calculated as a function of values for technical parameters. In some cases, these calculations involved weighting functions over tactical variables such as degree of target exposure. However, a laboratory scientist's choices concerning the variables to be considered or the weighting functions to be used, even if made with the advice and assistance of experienced soldiers, are unlikely to reflect the nuances, interconnections, and generalized fog of actual or adequately simulated combat.

In fairness to our predecessors in the technical V/L world, some of the factors that caused them to pursue these unsatisfactory practices should be mentioned. First, for perfectly good and understandable reasons, Army decision-makers craved analyses that illuminated military utility rather than narrower technical factors. Extant force-level models were not capable of using V/L metrics which were more complex. The generation of SSPKs was an attempt by the technical V/L community to respond to that demand, even if the attempt was intellectually misguided. Second, intellectually adequate combat simulations were simply not available until recently. (Some would argue that this overstates even our present capability.) Certainly through the 1970s, shortfalls in computer hardware capability and structured programming techniques were impediments to achieving adequate simulation capability. This situation provided further motivation for the technical V/L community to exceed its expertise and claim questions of military utility as within its domain.

The partly overlapping domains of the technical vulnerability experts and force-level modelers have caused further undesirable consequences with respect to the quality of our force-level efforts. One problem mentioned earlier is double counting. If a tactical variable such as target exposure is included by the vulnerability community in a utility measure such as SSPK, and then that SSPK is provided as input to a force-level model in which exposure is explicitly modeled, then there is evident double counting. Similar arguments can be made whenever scenario-type factors are built into the SSPK.

A second problem exacerbated by the overlapping domains is the loss-of-V/L-information problem due to excessive reliance on early averages. Typical SSPK values are highly averaged and are of relatively small value for illumination of specific cases. This is particularly troubling, as noted earlier, when the information needed to illuminate a special case was in fact available as an intermediate result.

A third problem with historical methods of attrition modeling in force-level contexts is the following. Use of a single quantity, be it an SSPK or something else, does not permit an accurate account of the remaining capability of the impacted target for many, perhaps for most, cases. The typical simulation draws a pseudo-random number and compares it to the input SSPK; the target either vanishes or remains fully capable depending on the results of the draw. Combat is actually much more complex, and we see in succeeding text that we can do much better.

EXAMPLE: PROPER V/L FORCE-LEVEL LINKAGE

We wish finally to give a clear illustration of the way in which V/L metrics (from **Level 2]** and **Level 3]**) can be used to link properly to a notional wargame. Our problem is to examine the vulnerability and mission effectiveness of a particular platform. As a specific example, we use an armored fighting vehicle such as a tank. This choice leads to a particular set of mission-critical components, mission-critical capabilities, and finally minimal mission requirements. However, this process can be applied to any military platform by appropriately tailoring the components, performance metrics, and mission requirements.

Before any damage occurs, we can represent the (null) damage vector at **Level 2]** as:

$$\mathbf{v_2} = (\square,\square,\square,\ldots) \quad . \tag{2}$$

The open squares ($\square$) represent the various undamaged components on the platform including crew, ammo, mission critical, and other. In today's high-resolution V/L simulations[15,16] a ground vehicle analysis utilizes on the order of 10^3 such components.

We can group the components by category to give the **Level 2]** vector $\mathbf{v_2}$ the form:

$$\mathbf{v_2} = (\underbrace{\square,\square,\ldots,}_{\text{Crew}}\ \underbrace{\square,\square,\ldots,}_{\text{Ammo}}\ \underbrace{\square,\square,\ldots,}_{\text{Fuel}}\ \underbrace{\square,\square,\ldots,}_{\text{Miss Crit}}\ \underbrace{\square,\square,\ldots}_{\text{Other}}\ ) \ . \tag{3}$$

We now invoke the sequence of operators portrayed in Fig. 1. We assume a shot is initiated at **Level 0]**; the resulting munition hit point is computed and passed to **Level 1]**. Next the $\mathbf{O_{1,2}}$ operator is used to compute a damage vector, $\mathbf{v_2}$. The effect of this action might be to transform the vector shown in Eq. (3) to the notional form:

$$\mathbf{v_2} = (\underbrace{\square,\blacksquare,\ldots,}_{\text{Crew}}\ \underbrace{\blacksquare,\blacksquare,\ldots,}_{\text{Ammo}}\ \underbrace{\square,\square,\ldots,}_{\text{Fuel}}\ \underbrace{\square,\blacksquare,\ldots,}_{\text{Miss Crit}}\ \underbrace{\square,\square,\ldots}_{\text{Other}}\ ) \ , \tag{4}$$

where, as before, the symbol $\blacksquare$ represents a killed component. The status of platform survivability now can be assessed. The number of killed crew members is known, the loss of ammo is known (along with an estimate of catastrophic loss of the platform), and the loss of fuel is known (along with an estimate of catastrophic loss of the platform). The status of Mission Critical components is known as well.

Next the damage vector shown at Eq. (4) is passed to the $\mathbf{O_{2,3}}$ mapper, where a **Level 3]** capability vector of the following form is computed:

$$\mathbf{v_3} = (\ \textbf{Mobility}, \textbf{Firepower}, \textbf{Commo}\ ) \quad . \tag{5}$$

For example, if one of the components killed is the box providing IFF† support, then the corresponding capability at **Level 3]** is lost as well.

This vector can be expanded into a more detailed expression of the form:

$$\mathbf{v_3} = (\{\mathbf{M_{TS}}, \mathbf{M_{MR}}, \mathbf{M_{RT}}\}, \{\mathbf{F_{ROF}}, \mathbf{F_{TTA}}, \mathbf{F_{HD}}\}, \{\mathbf{C_{INT}}, \mathbf{C_{EXT}}\}) \quad , \tag{6}$$

where $\mathbf{M_{TS}}$ is the vehicle Top Speed, $\mathbf{M_{MR}}$ is the Maximum Range, $\mathbf{M_{RT}}$ is the Rough Terrain capability, $\mathbf{F_{ROF}}$ is the main-gun Rate-of-Fire, $\mathbf{F_{TTA}}$ is the Time-to-Acquire (a target), $\mathbf{F_{HD}}$ is the Hit Dispersion, $\mathbf{C_{INT}}$ is the Internal Commo Capability, and $\mathbf{C_{EXT}}$ is the External Commo Capability. For descriptive ease, we can choose to represent these capability metrics as a fraction of the nominal (*i.e.*, undamaged) platform metrics. For the case of the tank being described, the capability vector of Eq. (6) can be illustrated in Fig. 4 in which Mobility, Firepower, and Communication functions are displayed.

In Fig. 4 (top), the three metrics of Top Speed (**TS**), Maximum Range (**MR**), and Rough Terrain (**RT**) capability are plotted on normalized scales. Full-scale value implies design or undamaged capability. The pointers to each metric labeled **AC** indicate the post-damage platform Actual Capabilities, respectively. Top Speed is at 80%, Maximum Range is at 80%, and Rough Terrain is at 60% of undamaged capability.

Figure 4 (middle) illustrates three Firepower metrics, Rate-of-Fire (**ROF**), Time-to-Acquire (**TTA**), and Hit Dispersion (**HD**). In this example the Actual Capability (**AC**) Rate-of-Fire is at 100% of the undamaged valued, the Time-to-Acquire is at 60%, and the Actual Hit Dispersion is at 20% of nominal value. This last metric corresponds to an *increase* in munition hit dispersion.

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15. Paul H. Deitz and Richard Saucier, *Modeling Ballistic Live-Fire Events*, **Proceedings of the 7th Annual TARDEC Symposium**, 26-28 March 1996, Monterey, CA; also appears in *Modeling Ballistic Live-Fire Events Trilogy*, **US Army Research Laboratory Technical Report ARL-TR-1274**, December 1996.

16. Paul H. Deitz, Richard Saucier, and William E. Baker, *Developments in Modeling Ballistic Live-Fire Events*, **Proceedings of the 16th International Ballistics Symposium and Exhibition**, 23-27 September 1996, San Francisco, CA; also appears in *Modeling Ballistic Live-Fire Events Trilogy*, **US Army Research Laboratory Technical Report ARL-TR-1274**, December 1996.

† *IFF* stands for *I*dentification *F*riend or *F*oe.

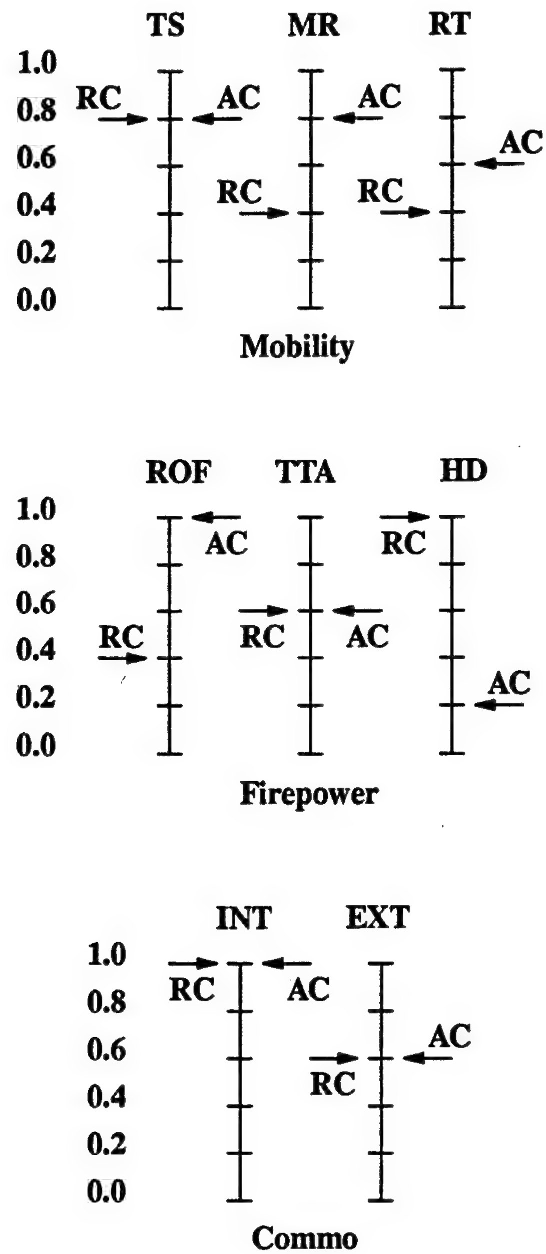

Fig. 4. Illustrative Examples of Actual versus (Mission) Required Platform Measures-of-Capability. Mobility graphs (top) illustrate three metrics, Top Speed (TS), Maximum Range (MR), and Rough Terrain (RT) capability plotted on normalized scales. The platform after-damage Actual Capability for each metric is indicated by AC. Firepower graphs (middle) illustrate Rate-of-Fire (ROF), Time-to-Acquire (TTA), and Hit Dispersion (HD). Communication graphs (bottom) illustrate Internal Communications (INT) and External Communications (EXT) capability. For a specific mission, each metric is rated in terms of a (minimum) Required Capability (RC). In order for the damaged platform to prosecute successfully the given mission, each Required Capability must be equaled or exceed by the corresponding Actual Capability.

Finally Fig. 4 (bottom) illustrates the platform Communication capability. In this case the Internal Communications (INT) Actual Capability is at full (100%) capability while the External Communications (EXT) is at 60% of undamaged capability.

Utility Mapping: Approach One

Note that the degraded performance capability described by Eq. (6) and illustrated in Fig. 4 arises as a direct consequence of the $\mathbf{O}_{2,3}$ operator operating on the non-null damage vector, $\mathbf{v}_2$, of Eq. (4).[□] As additional damage occurs to the platform, the damage vector of Eq. (4) is further populated, and the platform capabilities represented by Eq. (6) continue to diminish. On the other hand, if battle damage repair is initiated, then at least some of the component entries of Eq. (4) move from dysfunctional to functional, and the related platform capabilities of Eq. (6) increase. In other words, battle damage, whether initial or additional, populates the damage vector, $\mathbf{v}_2$, while battle damage repair acts to depopulate it.

The Mission Mapping Operator, $\mathbf{O}_{3,4}$, has to do with military utility, as was suggested previously, and is in the province of the force-level analyst rather than the technical V/L analyst. From a strategic point of view, there are two different lines of attack that historically have been followed to gain the objective of a credible $\mathbf{O}_{3,4}$ mapping.

One approach involves utilizing a group of experienced soldiers to consider a specified set of (presumably frequent or important) missions (≈ 10).[‡] For each specific mission, the experts decide the *minimum* capability for each metric required for a successful completion of the mission. The notional outcome of this process is illustrated in Fig. 4. The various **RC** pointers show the *minimum* platform Required Capabilities needed to complete successfully a *particular* mission.

Figure 4 thus illustrates that for the military platform to be successful for the specific notional mission, the following Required Capability (RC) metrics must be equaled or exceeded: Top Speed of 80%, Maximum Range of 40%, Rough Terrain capability of 40%, Rate-of-Fire of 40%, Time-to-Acquire of 60%, Hit Dispersion of 100%, Internal Commo of 100%, and External Commo of 60%.

The interpretation of the effect of platform damage on the ability to perform the mission is now clear. In this notional example, insofar as Mobility is supported, Top Speed is just adequate, the Maximum Range capability exceeds the minimum requirement, and so does the Rough Terrain capability. In terms of Firepower, the Rate-of-Fire minimum capability is greatly exceeded, the Time-to-Acquire requirement is just met, but the Hit Dispersion requirement is not nearly adequate (100% Required Capability needed *versus* 20% Actual Capability). Finally, both Communication Actual Capabilities are equal to the (Mission) Required Capabilities. In this example, the platform is not adequate to prosecute the mission because of the increased hit dispersion of the tank main armament. Such a situation might actually occur when a tank is engaged against a distant target; a greatly enlarged hit dispersion would substantially lessen the probability of hit.

Two final observations for this section. First, in addition to the comparison of the (Mission) Required/Actual Capabilities just discussed, the platform also must have had to pass the tests described below Eq. (4). That is to assure that no crew, ammunition, or fuel events resulted in catastrophic outcomes and, likewise, that no mission critical components were lost. Second, the general logic structure described in this report has already been implemented in the context of a personnel vulnerability evaluation tool. Called ORCA,[17,18] this computing environment plays multiple threats, as required, against a solider to compute [a] damage, [b] the effect of damage on various capabilities (*e.g.*, muscle strength/coordination, thinking, senses), and then [c] the capabilities compared against various mission requirements as called for in some 20 MOS's[*] comprising thousands of specific tasks.

□ Following Eq. (1), this relationship can be written:

$$\mathbf{v}_3 = \mathbf{O}_{2,3}\{\mathbf{v}_2\}$$

‡ What we now describe is somewhat reminiscent of the old Standard Damage Assessment List (SDAL) process but is constructed so as to avoid the broad averaging over many missions and the use of fractional capabilities as probabilities of mission success. For more detail on the SDAL construct, see Refs. 10 and 11.

17. Kellye C. Frew and Ellen M. Killion, *User's Manual for Operational Requirements-based Casualty Assessments (ORCA) Software System — Alpha+ Version*, Applied Research Associates, Inc., Report, Albuquerque, NM, July 1996.

18. J. Terrence Klopcic, David N. Neades, and Richard Tauson, *Operational Requirements-Based Casualty Assessment (ORCA) Methodology Documentation*, US Army Research Laboratory Technical Report, In Preparation.

* MOS stands for Military Occupational Specialty. Each specialty is used to define a set of supporting tasks which are used to set the minimum human capabilities needed for their successful prosecution.

Utility Mapping: Approach Two

The second line of attack is to use a combination of **Level 2]** and **Level 3]** vectors as input to a force-level model. The outcome metrics of the simulated combat are, in turn, regarded as reflecting the military utility force employed and key platforms in that force. By this process, the force-on-force model determines the success of a damaged military platform in a particular engagement. Given adequate (statistical) exercise of such a model, the minimum Requirement Capability (**RC**) levels for various platform capabilities can be backed out of the analysis. Experiments have been undertaken to develop this type of $\mathbf{O}_{3,4}$ map. The best documented of these force-level experiments are those of Comstock.[19] We invite the reader to study Comstock's results in detail; a brief overview is given here. This study involved configuring a small-unit force-level simulation to accept as V/L input either a traditional SSPK type of input or a distribution of more rigorously defined **Level 3]** capability metrics consistent with the V/L taxonomy. This strategy permitted a comparison of exchange ratios and other metrics as a function of the V/L input. Unsurprisingly, Comstock concluded that the more rigorous metrics provided ". . . a fuller and more detailed picture of combat . . . ." Also, Baker[20] showed that the procedures lead to results that are statistically dissimilar.

Utility Mapping: Conclusions

All three of the problems mentioned previously in connection with force-level modeling are solved or at least mitigated in the Comstock experiment. All traces of "utility" are purged from the **Level 3]** metrics (and not, of course, from the SSPKs). Much more of the information is retained in the Degraded States metrics than in the even more highly averaged SSPKs. Finally, the more rigorous methodology permits proper simulation of cases in which systems remain on the battlefield with some but not all of their original capability. This also provides support for wargame decisions based on reassignment of platform mission roles based on best match of roles, given new (reduced) capabilities.

Similar arguments could be made about a second experiment pursued by the Army Research Laboratory and the Training and Doctrine Command-White Sands Missile Range (TRAC-WSMR) over the past few years.[21] Although the results from that larger-scale force-level simulation have not yet been published, there appear no insuperable obstacles to pursuing implementation. With the promise shown in force-level modeling experiments since at least 1990, one might desire more rapid progress. No initiative is cost-free, and even low-cost initiatives are difficult to prosecute in a Defense downsizing environment. However, the delta cost on an ongoing business basis to work the force-level problem properly is moderate while the potential gain in information content high. We believe that there are no compelling reasons for not moving forward.

CONCLUSIONS

To summarize what we have argued with respect to the prosecution of V/L metrics as well as their use in a wide variety of applications:

- **Use of the V/L Taxonomy:** The V/L Taxonomy facilitates clear distinctions among the metrics of damage, capability, and utility that have often been confused. Specific outcome vectors at a given level are different from probability distributions formed from the corresponding family of outcomes. The probability of a given outcome is not equivalent to the utility of that outcome. These insights, as well as other derivatives of this framework,[□] are important in [a] the linkage of technology characterizations (*e.g.*, warhead/armor performance) V/L models, [b]

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19. Gary R. Comstock, ***The Degraded States Weapons Research Simulation (DSWARS): An Investigation of the Degraded States Vulnerability Methodology in a Combat Simulation,*** **US Army Materiel Systems Analysis Activity Technical Report AMSAA-TR-495, February 1991.**

20. **William W. Baker, *An Analysis of the Effect of the Degraded States Methodology for Vulnerability Assessment,* US Army Research Laboratory Memorandum Report ARL-MR-7, November 1992.**

21. **Beth S. Ward, Mark D. Burdeshaw, Joe L. Aguilar, and David R. Durda, *CASTFOREM Combat Simulation Utilizing Degraded States Vulnerability Methodology,* In Preparation.**

□ **For further discussion of the Taxonomy with respect to issues relevant both to generation of V/L metrics as well as configuration issues in force-on-force simulations, the reader is directed to Ref. 4.**

the internal consistency of V/L models including validation efforts in support of Live-Fire simulations,[22,23] and [c] the proper design and implementation of force-on-force models in which they play a critical role.

- **Minimization of Averaging:** Early averaging leads to significant loss of V/L information. The elements of damage and capability should be combined as late as practical in the overall computation process. Advances in computational equipment have not been fully exploited to avoid unnecessary early averaging.
- **Redundant Accounting:** Double counting is a problem that has historically affected the handoff from the technical V/L analyst to the force-level modeler. **Level 4]** technical V/L metrics have in the past been calculated as a function of tactics, doctrine, and scenario. Thus, a utility metric supplied by a V/L analyst is (re)introduced by a force-on-force modeler into a simulation which has as its primary purpose the estimation of utility. In particular, when a platform suffers equipment damage, and the value of that equipment varies significantly from mission to mission, the (expected) estimate of utility is likely to be in significant error.[‡]
- **Proper Aggregation of Battle Damage:** Current wargame practice accounts for multiple threats (whether ballistic or not) against a platform as though each threat encounters an undamaged platform. Except for the first impinging round, the initial conditions (**Level 1]** metrics) for the remaining damage mapping operations ($\mathbf{O}_{1,2}$) are incorrect. An aggregate utility is estimated through the use of the Survivor Rule on all of the individual (incorrectly) calculated utilities rather than simply aggregating damage as damage (at **Level 2]**), and then performing a single mapping to utility as needed.
- **Assignment of Battlefield Utility:** The job of estimating battlefield utility, $\mathbf{O}_{3,4}$, is for the wargamer, not the technical V/L analyst. **Level 2]** and **Level 3]** metrics should be used by force-level simulations in such a way that the military utility is estimated for a specific combat context. Both early averaging and double counting must be avoided.
- **Characterization of RAM and BDR:** The study of Reliability, Availability, and Maintainability (RAM) involves the same mapping procedure as damage calculation ($\mathbf{O}_{2,3}$). Battle Damage Repair (BDR) involves reducing the number of entries of the (**Level 2]**) damage vector. There would seem to be an opportunity to work both of these analyses with the aid of the vulnerability analyst using a shared set of naming conventions, data, and methods.
- **Opportunity for Wider Tool Sharing:** Proponents of Weapons Lethality and Platform Vulnerability often share tool sets and analysis approaches with effectiveness evaluators and with force-level analysts. However, their agendas are often diverse, leading to a wide range of required measures of utility and levels of detail. More interaction across the communities would probably reveal attainable improvements and greater efficiencies for all.

22. Gary S. Moss, Karen Ross Murray, and Richard Saucier, *Description of MUVES-SQuASH Methodology for Support of Live-Fire Test and Evaluation*, **Proceedings of the XXXVI Annual Meeting of the Army Operations Research Symposium**, 13-14 November, 1997, Fort Lee, VA; also **US Army Research Laboratory Technical Report**, In Press.

23. William E. Baker, Richard Saucier, Theodore M. Muehl, and Ricky L. Grote, *A Vulnerability Model Comparison to Live-Fire Test Results*, **Proceedings of the XXXVI Annual Meeting of the Army Operations Research Symposium**, 13-14 November, 1997, Fort Lee, VA; also **US Army Research Laboratory Technical Report**, In Press.

‡ Such an example might be a night-vision device for a tank. Presumably its utility at night (*e.g.*, Mobility Loss-of-Function) would be one, since the platform could not be fought without it. However in the day, it would be unneeded. Given equal weighting of both scenarios, the expected utility would be 0.5, greatly in error for either of the scenarios.

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13. ABSTRACT ***(Maximum 200 words)***

Beginning with World War II and its aftermath, the area of ballistic vulnerability/lethality (V/L) was first defined as a specific discipline within the field of ballistics. As the field developed, various practices and metrics emerged. In some cases metrics were developed that were abstractly useful but bore no direct relationship to field observables. In the last decade, as issues concerning Live-Fire strategies have gained importance, increased attention has been focused on V/L with the intent of bringing greater rigor and clarity to the discipline. In part this effort has taken the form of defining a *V/L Taxonomy*, which is a method of decomposing a series of concatenated complex processes into separable, less-complex operations, each with certain specifiable properties and relationships.

Using the Taxonomy, this report describes the most commonly used V/L metrics are a function of platform *aggregate damage*, reduced platform *capability*, and reduced *military utility*. We show that these three distinct and separable classes of metrics are linked by operators that are multivariate, stochastic, and nonlinear. We also show that it is useful to form probability distributions with respect to initial and boundary conditions in order to characterize damage, capability, and utility. Many defense community studies ignore these distinctions to the detriment of fundamental clarity. Examples are given and potential remedies described.

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5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______

CURRENT ADDRESS

Organization ______

Name ______ E-mail Name ______

Street or P.O. Box No. ______

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7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

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Organization ______

Name ______

Street or P.O. Box No. ______

City, State, Zip Code ______

(Remove this sheet, fold as indicated, tape closed, and mail.)

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